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# Azimuthal decorrelation in $t\bar{t}$ production at hadron colliders

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**ABSTRACT:** We present a new observable,  $\Delta\phi$ , an azimuthal angle difference between  $t$  and  $\bar{t}$  quarks in  $t\bar{t}$  pair production, at hadron colliders as an interesting probe of the radiative quantum chromodynamics process as well as a high-order correction in the high-mass regime. This variable also enables good discrimination on some new physics models that may explain the forward-backward charge asymmetry of  $t\bar{t}$  production measured at the Tevatron. With a reliable estimation of the dataset obtained up to 2011 at the Tevatron and Large Hadron Collider, we present an opportunity for testing the standard model as well as searching new physics models with the  $\Delta\phi$  observable.

**KEYWORDS:** QCD,  $t\bar{t}$ , Beyond Standard Model.

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## 1 Introduction

Azimuthal correlation of high transverse momentum ( $p_T$ ) jets is a valuable probe of the predictive power of quantum chromodynamics (QCD) and allows one to study QCD radiative processes. An accurate description of QCD radiative processes is crucial for a wide range of hadron collider measurements, including precision tests of the standard model (SM) as well as discoveries of new particles such as the Higgs boson and supersymmetry (SUSY) partners. In hadron colliders, the most common type of event is two-jet production with equal energies transverse to the beam direction such that the two jets are correlated in the azimuthal angle ( $\phi$ ) and the difference between the azimuthal angles of the two jets ( $\Delta\phi$ ) is equal to  $\pi$ . However, additional particles or jets including low-energy particles produced in the same event reduce  $\Delta\phi$  to less than  $\pi$ . Therefore, the measurement of azimuthal decorrelation provides an ideal test to understand the hard and soft radiative processes of QCD. Because of their importance, azimuthal decorrelations have been widely studied with inclusive two-jet production in various hadron collider experiments [1–3].

Understanding heavier quark production is particularly important because most new physics particles, which are usually quite heavy, decay into heavy quarks in the SM. The CDF Collaboration has measured the azimuthal angle decorrelation of bottom ( $b$ ) quarks from  $b\bar{b}$  pair production [4]. However, so far, there has been no measurement of the azimuthal decorrelation of top ( $t$ ) quarks, which are the heaviest known elementary particles. Measurement of  $t\bar{t}$  pair production and the radiative jet process is quite important for understanding higher order QCD effects with the heaviest elementary particle. These processes are important backgrounds to Higgs boson searches in electroweak vector boson fusion and  $t\bar{t}H$  production.

Measurements of the top quark had been limited by the relatively small cross section of  $t\bar{t}$  at the Tevatron, with an order of 1,000 events being listed in their full dataset. However, the Large Hadron Collider (LHC) has already obtained approximately  $5\text{ fb}^{-1}$   $pp$  collisions at  $\sqrt{s} = 7\text{ TeV}$ , corresponding to an order of 10,000  $t\bar{t}$  events, by taking advantage of the approximately 20 times larger production cross section. With large statistics of  $t\bar{t}$  events at the LHC, we can perform precision studies of the SM processes in the top sector. Even

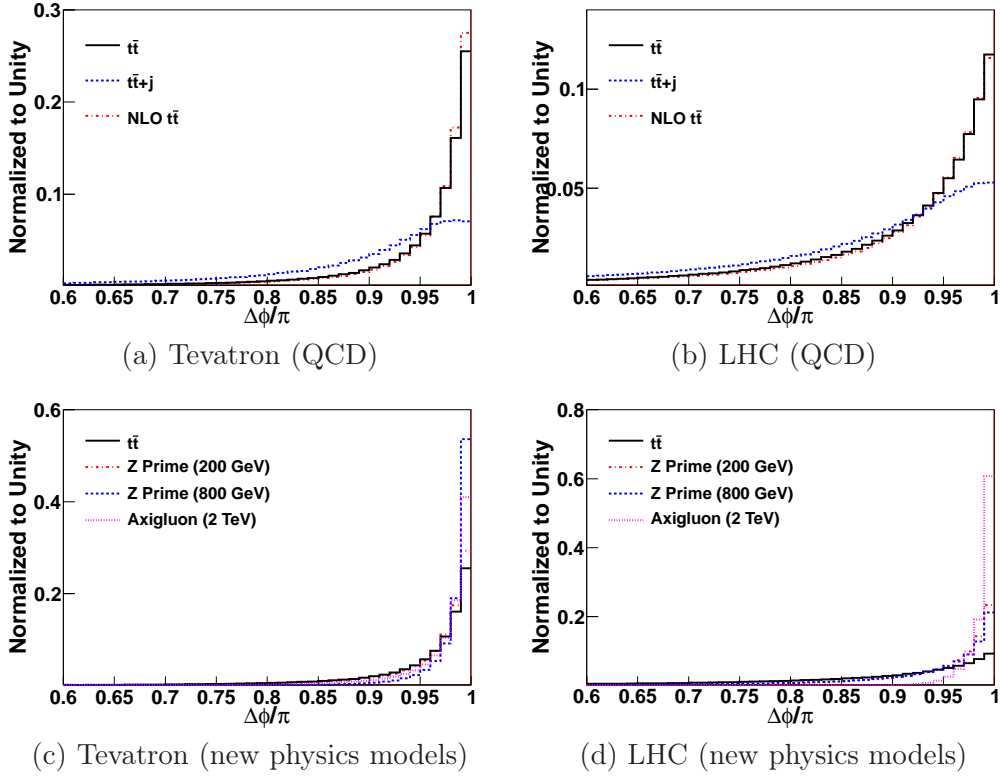
with limited statistics at the Tevatron, it is still interesting to study the feasibility of  $\Delta\phi$  measurement under different initial conditions using the full Tevatron dataset.

The top quark, the most recently discovered quark (in 1995 [5] at the Fermilab Tevatron  $p\bar{p}$  Collider), is the heaviest known elementary particle. Its large mass may indicate strong coupling with electroweak symmetry breaking, and therefore, the top quark is usually treated differently from the other light quarks in many new physics models. This suggests that many searches focus on the top quark signature. The recent observation of the charge forward-backward asymmetry at the Tevatron [6, 7] may be evidence for a new physics signature involved in  $t\bar{t}$  production. However, it seems hard to confirm the observation of new physics with a significance of 5 standard deviation from the SM with the limited statistics of Tevatron data even with the full dataset of  $10\text{ fb}^{-1}$  [8]. Since the LHC is a  $pp$  collider, it is difficult to probe all the possible scenarios of the Tevatron charge asymmetry at the LHC. It is even more difficult to distinguish the most relevant theories and parameters with the charge asymmetry measurement alone. The azimuthal decorrelation between  $t$  and  $\bar{t}$  quarks in  $t\bar{t}$  pair production is sensitive to additional radiation as well as the production mechanisms. Therefore, we expect it to be sensitive to new physics models and believe that it may provide an additional discrimination among the models related to forward-backward charge asymmetry at the Tevatron. In this Letter, we propose a new observable,  $\Delta\phi$ , the azimuthal angle between  $t$  and  $\bar{t}$  quarks in  $t\bar{t}$  pair production at the hadron colliders, for testing the SM as well as probing new physics models related to forward-backward charge asymmetry.

## 2 Models with parton level comparison

We generated simulated  $t\bar{t}$  signal samples using the leading order (LO) Monte Carlo (MC) generator MADGRAPH/MADEVENT package [9]. We generated signal samples for the inclusive production of  $t\bar{t}$  with all decay modes and a  $t\bar{t}$  with additional jets ( $t\bar{t}j$ ). Here most of additional jets in the  $t\bar{t}j$  sample were originated from initial- or final-state gluon radiations so that  $t\bar{t}j$  is the radiation-enriched sample. The higher order effects are taken into account by using the next-to-leading-order (NLO) MC generator POWHEG [10]. We generated 400,000 events in each sample for the Tevatron and 2,000,000 events for the LHC. To verify the distribution of  $\Delta\phi$  values from different processes, we generated plots comparing three different samples, as shown in Fig. 1(a) (Tevatron) and Fig. 1(b) (LHC). In these plots, we use parton level information of four vectors from  $t$  and  $\bar{t}$ . As already discussed,  $\Delta\phi$  is a variable sensitive to the radiation under conditions where the shapes corresponding to  $t\bar{t}$  and  $t\bar{t}j$  are well separated. However, the NLO samples have a distribution similar to that of the LO  $t\bar{t}$ . To achieve a precise understanding of the higher order effects using  $\Delta\phi$ , we may need a sufficient number of  $t\bar{t}$  events.

There are a couple of interesting models beyond the standard model (BSM) that can participate in  $t\bar{t}$  production. Each model is well motivated to explain the charge asymmetry at the Tevatron. For color-singlet heavy bosons, such as  $Z'$ , mediated production is one of the most interesting scenarios [11]. However, the measured constraints on  $Z'$  from dijet production at the LHC already surpass the TeV scale [12]. Also, a heavy resonant  $Z'$  cannot



**Figure 1.** (Color online) Parton level comparison of various models at the Tevatron and LHC.

explain the total cross section of  $t\bar{t}$  at the Tevatron, which is in excellent agreement with that of the SM. To avoid this issue, low-mass-vector-boson-mediated production is popular [13]. A direct search for low-mass vector bosons, such as  $Z'$ , is very difficult because of the low production cross section as well as large SM backgrounds. For our study of the  $\Delta\phi$  observable, we generated simulated signal samples for low-mass, nonresonant  $t\bar{t}$  production from 200-GeV  $Z'$  bosons. We also generated samples for the decay of 800-GeV resonant  $Z'$  production into  $t\bar{t}$  as a benchmark model. We consider massive color-octet vector boson production, for which there are well-motivated theories to explain the charge asymmetry at the Tevatron [14], such as axigluon models [15], technicolor models [16], and extra-dimensional models with KK gluons [17]. Even though the LHC has started investigating dijet resonance in the TeV scale, it is not yet able to probe the color-octet vector bosons associated with the electroweak symmetry breaking sector, as suggested by several of the models discussed above. As a benchmark model for color-octet vector boson production, we generated signal samples for 2-TeV axigluon-mediated production decaying into  $t\bar{t}$ . We used the MADGRAPH/MADEVENT package with the top-BSM model [18] to generate these new physics models.

We compare the  $\Delta\phi$  distribution from new physics models with SM  $t\bar{t}$  in Fig. 1 (c) (Tevatron) and Fig. 1 (d) (LHC) using parton level information. The new physics models are clearly separable from the SM  $t\bar{t}$  in most of the models for both the Tevatron and the LHC. At the Tevatron, heavy  $Z'$  production exhibits the most visible difference with the

**Table 1.** Expected numbers of signal and background events at the Tevatron with  $10 \text{ fb}^{-1}$   $p\bar{p}$  collisions and at the LHC with  $5 \text{ fb}^{-1}$   $pp$  collisions.

	Tevatron, $10 \text{ fb}^{-1}$	LHC, $5 \text{ fb}^{-1}$
$t\bar{t}$ signal	$1859 \pm 189$	$46527 \pm 1173$
Background	$516 \pm 110$	$11459 \pm 2345$

SM  $t\bar{t}$ , and the 2-TeV axigluon is also clearly distinguished. However, the 200-GeV  $Z'$  shows a relatively small deviation from the SM  $t\bar{t}$ , which indicates that we may need larger event statistics to separate this new physics model from the SM. At the LHC, the difference is more marked. The three new physics models are clearly separated from the SM. In addition, we can take advantage of the large cross section at the LHC, which would provide us a much better opportunity to detect new physics with  $\Delta\phi$ . We investigated, in detail, the realistic situation after carrying out detector simulations as well as event reconstruction. We assume the number of events to be  $10 \text{ fb}^{-1}$  at the Tevatron and  $5 \text{ fb}^{-1}$  at LHC, which were already obtained by last year.

### 3 Models with detector simulation

It is important to consider the effect of detector resolution and data statistics as well as the background contributions for a realistic prediction of the measurement. The parton level information of each model generated with MADGRAPH/MADEVENT and POWHEG has undergone parton showering and hadronization using PYTHIA [19]. The detector effects are taken into account by using the fast detector simulation package PGS [20]. The detector resolution effects are simulated using the following parameterization:

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \text{ for jets,}$$

$$\frac{\delta E}{E} = \frac{b}{\sqrt{E}} + c \text{ for leptons.}$$

As per the predefined values in the PGS package, we considered  $a = 0.8$ ,  $b = 0.2$ , and  $c = 0.01$  for the Tevatron and  $a = 1.25$ ,  $b = 0.03$ , and  $c = 0.01$  for the LHC. The PGS package can also quickly reconstruct each physics object such as leptons, jets, and missing transverse energy. Jets originating from  $b$  quarks are tagged with approximately 40%  $b$ -tagging efficiency. The expected signal and background events with one or more  $b$ -taggings are taken from the Tevatron  $4.8 \text{ fb}^{-1}$  measurement [21] and the LHC  $1.1 \text{ fb}^{-1}$  measurement [22]. The expected events with Tevatron  $10 \text{ fb}^{-1}$  and LHC  $5 \text{ fb}^{-1}$  are scaled based on the luminosity increase. Background events are also modeled with the MADGRAPH/MADEVENT package. To simplify the analysis, we only consider the major background, from  $W$ +jets, as the shape of the full background. Table 1 shows the expected signal and background events at the Tevatron  $10 \text{ fb}^{-1}$  and LHC  $5 \text{ fb}^{-1}$ .

By assuming unitarity of the three-generation quark-mixing CKM matrix,  $t$  and  $\bar{t}$  quarks decay almost exclusively into a  $W$  boson and a bottom quark [23]. The case in

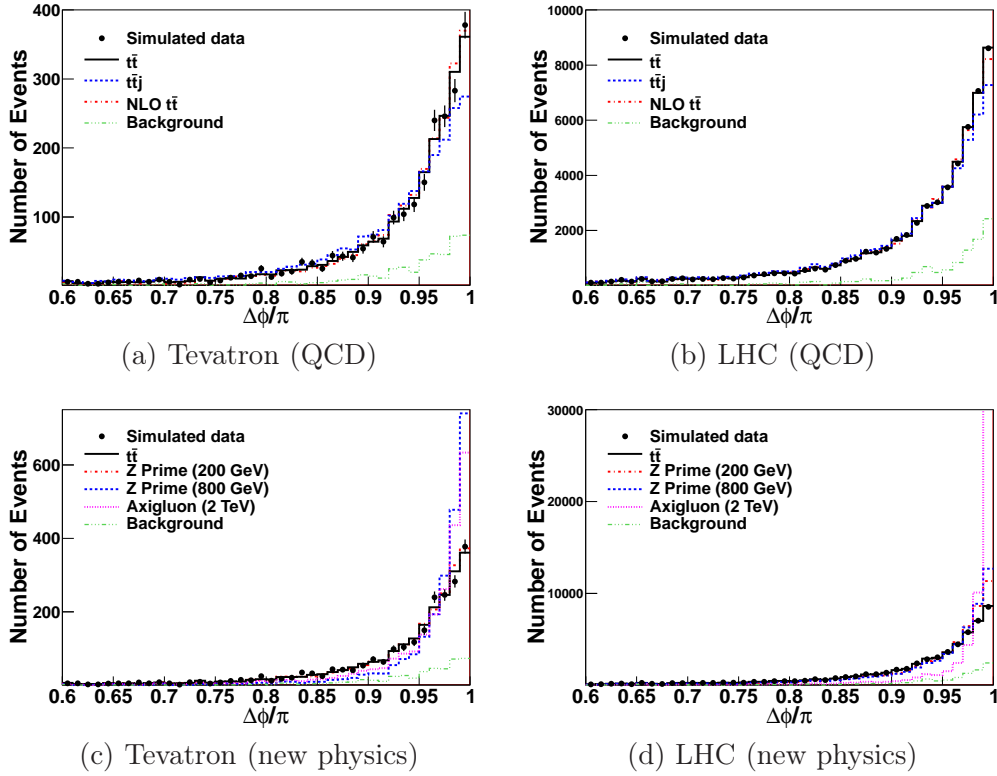
which one  $W$  decays into a charged lepton and a neutrino and the other into a pair of jets defines the lepton+jets decay channel. After the fast simulation, we select the events corresponding to the lepton+jets decay topology. We require exactly one isolated electron or muon with  $E_T > 20$  GeV or  $p_T > 20$  GeV/ $c$ . We also require large missing transverse energy,  $\cancel{E}_T > 20$  GeV, and at least four jets with  $E_T > 20$  GeV. We request at least one jet to be tagged.

The reconstruction of  $t\bar{t}$  production is particularly important for estimating  $\Delta\phi$ . In the lepton+jets final state, the top quark momenta and neutrino momentum are fully reconstructed because the system is overconstrained by the well-known  $W$  boson mass of 80.4 GeV/ $c^2$  [24] and the  $t$  quark mass of 173 GeV/ $c^2$  [25]. However, the ambiguity of jets-to-partons assignments introduces complications in event reconstruction and results in a smearing of the resolution. To obtain the most probable combination as well as to calculate the neutrino momentum, we build a  $\chi^2$ -like kinematic fitter. The form of the kinematic fitter used in this reconstruction is very similar to that used in the CDF measurements [26]. However, because of the lack of raw detector information in the fast simulation, we directly use  $\cancel{E}_T$  instead of the unclustered energy with the conservative assumption of approximately 40% resolution. We then define  $\chi^2$  for the kinematic fitter as

$$\begin{aligned}\chi^2 = & \Sigma_{i=\ell, 4jets} (p_T^{i,fit} - p_T^{i,meas})^2 / \sigma_i^2 \\ & + \Sigma_{k=x,y} (\nu_{T_k}^{fit} - \cancel{E}_{T_k}^{meas})^2 / \sigma_k^2 \\ & + (M_{jj} - M_W)^2 / \Gamma_W^2 + (M_{\ell\nu} - M_W)^2 / \Gamma_W^2 \\ & + \{M_{bjj} - M_{\text{top}}\}^2 / \Gamma_t^2 \\ & + \{M_{b\ell\nu} - M_{\text{top}}\}^2 / \Gamma_t^2.\end{aligned}$$

In this  $\chi^2$  formula, the first term constrains  $p_T$  of the lepton and the four leading jets to their measured values within their uncertainties (detector resolutions); the second term does the same for both transverse components of  $\cancel{E}_T$ ,  $x$  and  $y$ , as well as those of the neutrino,  $p_x$  and  $p_y$ . The remaining four terms, the quantities  $M_{jj}$ ,  $M_{\ell\nu}$ ,  $M_{bjj}$ , and  $M_{b\ell\nu}$ , refer to the invariant masses of the four-vector sum of the particles denoted in the subscripts.  $M_W$  and  $M_{\text{top}}$  are the masses of the  $W$  boson (80.4 GeV/ $c^2$ ) [23] and the  $t$  quark (173.0 GeV/ $c^2$ ) [25], respectively.  $\Gamma_W$  (2.1 GeV/ $c^2$ ) and  $\Gamma_t$  (1.5 GeV/ $c^2$ ) are the total widths of the  $W$  boson and the  $t$  quark, respectively [23].

To demonstrate the expected distribution of data from each collider experiment, we randomly select the signal and background events from LO  $t\bar{t}$  and  $W$ +jets background corresponding to the expected signal and background events in Table 1. We call these events the “simulated data.” Figure 2 shows the azimuthal decorrelation distribution of the simulated data compared with various physics processes normalized to the expected events. The comparisons with SM processes are shown in Fig. 2(a) (Tevatron) and Fig. 2(b) (LHC). As one can see in Fig. 2(a), it is almost impossible to distinguish high-order effects (NLO  $t\bar{t}$ ) from LO  $t\bar{t}$  at the Tevatron. However, the  $t\bar{t}j$  sample has a very distinct shape for the  $\Delta\phi$  distribution, so we can study radiative QCD effects at the Tevatron. As shown in Fig. 2(b), the large statistics of the LHC allow us to discriminate NLO  $t\bar{t}$  from



**Figure 2.** (Color online) Data (simulated) compared with various models at the Tevatron and LHC with detector simulation and event reconstruction.

LO  $t\bar{t}$  above the statistical fluctuation. Studying the higher order effect using LHC data would be interesting. One can also see a clear difference between the  $\Delta\phi$  distributions of  $t\bar{t}$  and  $t\bar{t}j$  samples with LHC data, which would allow a precise study of the radiative QCD process in the high-mass regime.

The  $\Delta\phi$  distribution from various new physics models are shown in Fig. 2(c) (Tevatron) and Fig. 2(d) (LHC), respectively. As one can see in these figures, most of the models are well distinguished from the SM ( $t\bar{t}$ ). With  $10 \text{ fb}^{-1}$  Tevatron data, it is clear that we can perform interesting studies for the 800-GeV  $Z'$  and 2-TeV axigluon models using the  $\Delta\phi$  distribution. Depending on the fraction of new physics production in the  $t\bar{t}$  signature, we may be able to obtain significant hints related to new physics models at the Tevatron. However, it seems difficult to study low-mass vector boson (200-GeV  $Z'$ ) production using  $\Delta\phi$  at the Tevatron because the shape is very similar to that of the SM and the event statistics are inadequate to discriminate between them. At the LHC, there are huge differences between the shapes of the  $\Delta\phi$  distributions, not only between the shapes of the new physics models and the SM but also among those of the new physics models themselves. It is possible to detect a small contribution of the new physics signature under the dominant SM  $t\bar{t}$  processes. Depending on the new physics cross section, the underlying physics model related with the charge forward-backward asymmetry can be studied with the  $\Delta\phi$  observable. Because  $\Delta\phi$  information is not fully correlated with the charge forward-backward asymmetry,  $\Delta\phi$  can



give additional information about the new physics signature.

## 4 Conclusion

In conclusion, we propose an interesting new observable,  $\Delta\phi$ , the azimuthal decorrelation between  $t$  and  $\bar{t}$  quarks in  $t\bar{t}$  pair production, at hadron colliders as an interesting probe to study the SM precisely as well as to search for new physics related to the forward-backward charge asymmetry at the Tevatron. With  $10 \text{ fb}^{-1}$   $p\bar{p}$  collisions at the Tevatron, the possibilities for studying SM processes as well as searching for new physics signature are demonstrated. In the LHC, the large number of  $t\bar{t}$  production events using  $5 \text{ fb}^{-1}$   $pp$  collisions allows a precision study of the SM QCD processes as well as offers a huge discovery potential for new physics signatures. Together with the charge forward-backward asymmetry information, the  $\Delta\phi$  observable can be used to discriminate underlying new physics theories.

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